PROGRESS REPORT

Seventeenth - Eighteenth Quarter

June 1, 1965 - November 30, 1965

LOW-POWER, LOW-SPEED DATA STORAGE AND PROCESSING TECHNIQUES

National Aeronautics and

Space Administration

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DEPARTMENT OF ENGINEERING

AND APPLIED SCIENCE

YALE UNIVERSITY

PREFACE

The following is the ninth Progress Report on the National Aeronautics and Space Administration Research Grant NsG-138-61, entitled "Low-Power, Low-Speed Data Storage and Processing Techniques." It covers the Seventeenth and Eighteenth quarters beginning June 1, 1965.

The work will be covered by descriptive reports outlining the progress and direction of the research and will state in simple terms the important conclusions. Detailed technical studies will be published in a series of Technical Notes as soon as they are completed.

Richard Clark Barker
Director

STATEMENT OF OBJECTIVES

The purpose of this research is to improve the technical capability to perform memory functions in spacecraft. The study includes special purpose, preprogrammed memories, memories that perform data-analysis functions, and general-purpose memories, including content-addressed and command-addressed memories.

At the present time, the demands of spacecraft development schedules require early commitment to developed memories and well-established circuit techniques. The research covered by this grant is designed to bring together the newest techniques and materials in a manner relevant to spacecraft application so that improvements in memory designs can be realized from basic technical advances as rapidly as possible. The results should be applicable to a wide variety of spacecraft missions.

An important part of the study is to assemble information on a variety of memory techniques so that it will be available to NASA instrumentation groups and associated groups planning space experiments.

SUMMARY OF WORK FOR THE SEVENTEENTH AND EIGHTEENTH QUARTERS

New Devices

During this period, approximately half of our effort has been put into the study of electron tunneling devices. This is about 80 per cent devoted to experimental work, part of which was involved with developing techniques for evaporating or growing films, and the remainder measuring the characteristics of tunnel junctions and comparing them with those predicted from theory.

1. Vacuum systems

In June, we were still operating with the original three systems. One was a new Varian Vac-Ion pump with Vac-Sorb roughing pumps and a titanium sublimation pump. This operates with a 12-inch glass bell jar and a MRC 8-port feedthrough collar. The system can maintain mid-10^{-7} range pressure while evaporating Nickel. We have had some difficulty in cycling because the roughing pumps did not get the pressure low enough to keep the Vac-Ion pump from over-heating. The second system was the 10-year-old 12-inch system given to us by IBM as surplus equipment. It delivers not much better than 10^{-5} Torr in the bell jar during evaporation, which is adequate for some of the sputtering work. The third was a 1948-vintage Distillation Products pump with an 18-inch bell jar, which we hoped to put into service. After much effort, we obtained not better than 10^{-5} Torr in the bell jar, so the system was scrapped except for the jar, stand and hoist.

Since there is some urgency for a system which can do multiple operations without breaking the vacuum and contaminating the surfaces, we have saved the bell jar, the hoist and the stand, built our own base plate and roughing lines, and installed a new HVECo 6" diffusion pump and a new roughing pump. The roughing pump has a 1-micron capability, as opposed to the 40 microns of the early system. The system has a gate valve just below the base plate so that the diffusion pump can be left on while the vacuum is broken. It also roughs through the baseplate, which is essential when the gate valve is used. With the addition of a titanium sublimation pump of our own design in the bell jar, we can now go from atmospheric pressure to $5{:}10^{-7}$ Torr in about 15 minutes, with liquid nitrogen in the collant baffle. Delivery of the pump was promised in the middle of June. It was three weeks late, there was a low-temperature leak in the nitrogen baffle, there was time involved in the set up, the low-pressure plumming, delivery of the vacuum gauges, and in completing the automatic protection system which turns off the pump power if the pressure gets above limits. As a result, the system was put in operation in mid-October. Also nearly complete are a titanium sublimation pump designed to fit in the top of the bell jar, a substrate heater and holder, and an electron bombardment evaporation source.

2. Preparation of Samples.

The experiments to date have involved tunneling through thin oxide layers between two different metals. We are aiming at tunneling between copper and nickel. Therefore, the materials being prepared are of three kinds: nickel, oxide and copper.

<u>Nickel</u>

We are evaporating pure nickel from an electron bombardment source of our own design. The power supply is a $10,000 item if bought commercially. We were fortunate enough to obtain schematics of a unit designed by an industrial research laboratory, a parts list and some hints on layout. As a result, we built the unit for about $1, 200 in parts and had less than a day of debugging and checking out, which is remarkable. The unit contains a 5.000-volt, 1-ampere supply for the beam, and a 25-volt, 40 ampere supply for the filament. One of the major features of the source is that the high voltage supply is current stabilized. The vapor of the evaporated material tends to ionize and produce gross instabilities in the operation of the electron beam source. The current stabilization permits continuous beam current control through a much wider range.

In parallel with the evaporation of nickel, we are also working with single crystals. These are being prepared by the vapor growth method, and by slicing quarter-inch cylindrical crystals parallel to the desired crystal faces.

The growth of the crystals in the vapor takes place at approximately 700 degrees centigrade. About ten grams of nickel bromide are placed in one end of a small procelain crucible which is covered with a similar crucible chipped along the sides to permit an equilibrium flow of the atmosphere. Nitrogen is fed into one end of the tube at about 100 cc/min and a very small amount of hydrogen, approximately 0.1 cc/min (almost impossible to measure) is added. Reduction of the NiBr takes place in the vapor and platelets and whiskers grow on imperfections on the porcelain surfaces. We have had some problem getting just the right combination of parameters in the dishes with the result that crystals do not always grow. The lack of reproducibility of growth makes us doubt that we understand fully the conditions required. This is admittedly a highly empirical science. Thus, our efforts have been directed at controlling the atmosphere, flow, and temperature in the region of crystal growth so that the number of unknowns can be reduced. Platelets of about 100 microns in size, triangles and rectangles, about 1000 angstroms thick, are being grown sproatically. We occasionally find some in the millimeter size.

For the sliced crystals, procedures have been worked out for polishing the surfaces, mounting the crystal in a goniometer head, obtaining the orientation by X-ray Laue patterns, and slicing parallel to the desired face. Whereas the samples are much larger than the platelets, the perfection of the surface is much greater by any measure in the platelets. Copper crystals have been prepared in the same way. Having established the process adequately, we are making no more wafers until the method of growing the oxide has been satisfactorily developed.

Oxides

The intermediate oxide should be in the range between 20 and 100 angstroms. This is very hard to measure. Further, it is suspected that normal surface irregularities on an oxide may be expected to be of the same order of thickness. The oxides grown have been nickel oxide and aluminum oxide. The temperature for the growth of nickel oxide and aluminum oxide are very different. Aluminum will oxidize to at least 20 angstroms at room temperatures, whereas nickel requires a much higher temperature (about 300 C). The aluminum oxide profile should, therefore, be relatively easy to define on top of the nickel.

However, in 20 A thick films, it is difficult to obtain aluminum oxide without pinholes since it grows on a nickel surface. We have attempted to oxidize the existing nickel in the hope of obtaining a continuous nickel oxide film.

Aluminum oxide has been made by evaporating aluminum and then oxidizing, evaporating aluminum oxide directly, and evaporating aluminum in an oxygen atmosphere. The nickel oxide has been grown by oxidizing the nickel surface at elevated temperatures in an oxygen atmosphere, and by means of a glow discharge. The glow discharge technique has given by far the best results.

Copper

In most of the early experiments, copper was evaporated over the oxide layer to form the second metal surface. The copper strips were brought out to the side where solder contacts were made. The copper was evaporated with the electron gun source. It was discovered that the copper was being in part ionized, although the ions were apparently being driven through the very thin oxide layer and causing short circuits. For some time, it was thought that the short circuits were caused by faulty oxides. Experiments have since established that the ionized copper was at fault. The copper is now being evaporated from a hot filament. It was also discovered that if the substrate was heated during evaporation of the copper, the additional mobility of the copper and the oxide also caused short circuits. Successful junctions require that the substrate be kept at room temperature and that the copper be evaporated by a technique which does not ionize the material. The substrate temperature can be and may have to be controlled.

3. Tunneling Experiments

It should be obvious that in addition to the tunneling experiments themselves a great deal remains to be understood about the character and formation of the oxides which are central to the study of any electronic processes at surfaces. We are attempting to be selective about the aspects of the oxides we study, selecting only those aspects that affect our immediate ability to make good reproducible tunnel junctions.

From this standpoint, we believe that the measure of the quality of the oxide is our ability to match the tunneling equations of Simmons. The major unknown in matching these equations is the active area of the junction. If the surfaces are rough, the majority of the tunneling will take place over a small portion of the junction.

Junctions have been made by simply crossing strips, with an oxide over the first one. We have also masked off a thin strip on a wider one by evaporations of silicon monoxide, shadowing the strip with a thin wire. This has been done on top of the oxide, and also the nickel has been oxidized through the masked-off strip. Experiments have not yet been sufficiently conclusive to compare these methods, but it appears to be a matter of convenience as far as our experiments are concerned. For extensive production of junctions, it will be a matter of technological development.

4. Device Objectives.

From time to time it is helpful to restate in broad terms the objectives of the work in this portion of our program. We are attempting to devise new methods of reading out memory devices. It is our opinion that the most significant advances of this kind are to be found in the form of macroscopic quantum effects: effects that are not predicted by classical physics. It is further our opinion that useful effects of this kind are likely to be found at the interfaces of different materials in the form of interactions between electrical, magnetic and optical properties.

In the present studies, we are looking for a variation of conductivity resulting from a shift in the band structure in magnetic films. Doing the experiments requires that we develop a capability of making metal films, single crystals, oxides and other supporting masking and insullating processes. It also requires that we study conduction and magnetization processes in terms of quantum theory from the standpoint of useable devices. As a result, we hope to be able to develop our capability to examine various experimental configurations and be able to assess which ones are likely to degenerate to classical, known phenomena, and which ones will show quantum effects in a macroscopic form.

While we are being very deliberate in what we are attempting to do in the short run, we are realistic about what to expect. It rarely happens, if ever, that one sets out to invent the transistor and succeeds. However, the short-range objectives we have set for ourselves are a direct challenge to translate the physics into useable form and either do it or show by sound reasoning from first principles why it cannot be done.

There are relatively few people who are attempting to develep radically new memory techniques. Although our efforts are far removed from product development, we believe that the need to apply new technology in the memory field justifies this kind of research in a memory-systems oriented program. Further, since we are concentrating our efforts on techniques that are qualitatively different and are based on the applied physics from which the next generation of technology will come, we believe that this kind of effort constitutes ideal university research. It should be clearly understood that graduate students working in this program began their graduate work two to three years ago with their interests centered on classical electronic techniques and circuit analysis. Today they are graduating with experience in the latest thin film technology and with a working knowledge of the quantum theory of electronic processes. We contend, therefore, that the research efforts have an impact on the space program that far exceeds the specific developments that may come from our laboratories.

Properties of Ferrites and Ferrite Devices

Our paper, Measurement of Useful Properties of Memory Devices, summarizes the types of experimental work in progress. At this stage in the development of magnetic memory, it might be wondered what more can be measured on a little ferrite ring. The above paper summarizes what we believe is required to characterize a core from a memory standpoint. In practice, data is never as complete as this.

There is still a great deal of mystery surrounding the nature of the physical processes that take place during the reversal of magnetization at high speeds. The theoretical and experimental approaches to these questions have become highly stylized, and rather ineffective. Many have ceased to work on the problem, some because it is too difficult and some because industrial development of ferrites has proceeded satisfactorily and is not likely to gain from theoretical research in proportion to its cost. The increasing use of memory has been responsible for a proliferation of companies competing in the field. The price competition has produced a cutback in basic research and a concentration of effort on production processes, quality control, and cost reduction. The situation is similar to that in the semiconductor industry.

Our efforts are aimed at developing a new and more revealing approach to these studies. The physical processes involved in magnetic switching are governed by grain size, grain interfaces, voids, variation of chemistry through the volume due to oxidation or reduction in the firing atmosphere, anisotropy of the basic ferrite material, and internal stress due to surface shrinkage in the firing process. The question is: in what relative proportion do these properties affect the measured electromagnetic characteristics, and by controlling these properties, what characteristics can be enhanced or diminished. Our specific interest is in nondestructive readout properties.

1. Theory

Studies are being made to review existing theories from which one can estimate relative amounts of energy involved in magnetostatic fields, anisotropy, and domain walls statically, and accoustic and spin waves dynamically. Known properties of the materials are being accumulated to enable us to make quantitative calculations. We are especially interested in evaluating temperature dependence of the various energy components. Temperature dependent measurements may make it possible to separate the contributions of the constituent energies experimentally.

The theoretical work is difficult and time-consuming. Although we do not have full command of the situation as yet, progress has been made.

2. Experiment

In order to make any experimental contribution to our understanding of magnetization processes, it is necessary to make accurate quantitative measurements. Measurements typically made of switching waveforms are of 5 to 10 percent accuracy and highly qualitative in concept. We have, therefore, made a substantial effort to mechanize the data-taking so that it can be recorded permanently in a suitable form. In recent months primary experimental efforts have been devoted to the instrumentation. The instrumentation has become sufficiently complex to merit a technical memorandum, which will be published soon.

Instrumentation

1. Pulsers

A prototype pulser design was completed during the spring term. Many pulsers are needed for some of our pulse programs, and at $750 each, the cost justified construction of some laboratory units. The pulser was designed by a senior student as a laboratory project. It delivers 50 volts into a 50-ohm load, variable in 2 db steps. The pulse has a variable rise time which can be reduced to 75 nsec., which is adequate for many applications. It is triggered externally, and has a pulse delay up to 1 msec and a pulse width variable up to 1 msec.

During the summer the prototype was debugged, parts were ordered, copper circuit boards were printed, and ten units were constructed. Final tests have been completed and drawings have been made.

2. Programmers

The logic of the first unit has been redesigned to improve oscillator burst control and include a program stop. A second unit has been constructed using DEC Flip Chip components, which fits on a 19- by 6-inch panel. Its front panel features include:

-- Reset, run, single step, and program stop

— 16 clock times, 8 outputs. All timing done on a 6-inch square matrix with diode pins.

— Four delay units for two step repeats, two pair repeats. Delays up to one second. Gates for oscillator burst control are available at the front panel for all delays.

-- One step-repeat delay is switched to an "Inhibit Stop" mode in which it inhibits the program stop for the period of the delay. This allows one to set the program stop and, by pressing the start button, to go through a variable number of complete cycles before activating the program stop.

-- One pair-repeat delay can be switched to a Quad Repeat mode, allowing one to repeat a set of four pulses rather than a pair for the duration of the delay.

This unit is essential for some of the experimental studies planned. Commercial versions are priced near $6000. This unit was built at a parts cost of $1600.

3. Magnetic Characteristics

Modifications have been made to the 567 sampling scope to plot the trace directly on an X-Y coordinate pen recorder. A Type O plug-in unit has been adapted to the 567 to integrate the sampled signal in order to plot flux. On repetitive testing, this reduces the need to integrate high-speed waveforms accurately. As a result, ϕ - F characteristics can be recorded in a size and format suitable for making quantitative measurements.

PLANS

There are several projects that have been somewhat delayed, primarily because of personnel changes, and will be completed in the next quarter.

1. The 90 per cent-complete study of the characteristics of an adaptive telemetry system using bit-plane encoding or other data-compression schemes. This is the thesis of R. M. Lockerd, who found it necessary to leave Yale. He has not yet completed the work.
2. The model bit-plane encoding memory, which is also 90 per cent complete and was suspended when Lockerd left. We have not had readily assignable manpower to complete the remaining portions of the timing circuits, but intend to complete them during the next quarter.
3. An experimental study of a magnetic threshold pulse counter was made during the spring term as a student project. A second design is required in order to improve the count threshold from 20 to the desired 32. This will be completed and written up in the next quarter.

Work on thin film devices and ferrites will continue as indicated above. We are hopeful that we will have some significant results to report in the next few months.